CURRENT COMPOSITION AND STRUCTURE OF A DISJUNCT EASTERN HEMLOCK ECOSYSTEM IN NORTHWESTERN ALABAMA AND MODELING POTENTIAL HEMLOCK WOOLLY ADELGID INFESTATION

Undergraduate Honors Thesis

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ABSTRACT

Eastern hemlock (*Tsuga canadensis* (L.) Carr.) is a coniferous tree species native to a large portion of the eastern United States, and it is important in its role as a foundation species and in its contribution to landscape biodiversity. The southernmost populations of hemlock occur in Alabama, and these populations are unique in that they are disjunct from the main range of hemlock that has its southernmost point in northern Georgia. Unfortunately, the hemlock woolly adelgid (*Adelges tsugae* Annand; HWA), an invasive insect native to Japan, has been causing extensive hemlock mortality since the insect's accidental introduction into the United States in 1951. This insect has caused the rapid decline of hemlock throughout the South but as of this time has not reached Alabama. The hemlock populations of Alabama will likely be among the last hemlock-dominated forests in the South to be impacted by HWA. It is hypothesized that the geographic location of this forest ecosystem type makes it highly susceptible to HWA infestation that would significantly alter the forest's successional trajectory.

The objectives of this study were to: 1) examine the current composition and structure of a disjunct eastern hemlock ecosystem type in northwestern Alabama, and 2) model the effects of hemlock mortality from HWA infestation at this southern boundary of the hemlock's range using the U.S.D.A. Forest Service Forest Vegetation Simulator (FVS) and the Hemlock Woolly Adelgid Event Monitor. This study serves as a baseline to inform future HWA management efforts in the region.

Plot sampling was performed during May 2015 in two hemlock-dominated stands on the William B. Bankhead National Forest in northwestern Alabama. Quantitative measurements of the woody plants, physiography, and soil were collected on a total of ten 200-m^2 plots. Hemlock

dominated the overstory (49% importance value; IV), although oak species (i.e., *Quercus montana*, *Quercus alba*, and *Quercus coccinea*; combined 27% IV) were also prevalent. Hemlock also dominated the large sapling size-class (49% relative density), though deciduous species (e.g., *Quercus montana* and *Acer rubrum*) dominated the smaller size-classes in the understory. The A-horizon of the soil in the study area was acidic with a pH range of 4.5-6.5, and steep northerly aspects characterized the physiography of the study area, with slope gradients ranging from 20-35%.

The FVS model predicted that the initial HWA infestation in the study area will occur between 2024 and 2027, and with a decline in hemlock basal area >99% by the year 2060. Total basal area of the forest was forecast to remain relatively unchanged, and it was predicted that deciduous tree species (e.g., *Quercus montana* and *Quercus alba*) will replace hemlock when an HWA infestation occurs. This shift from a coniferous forest ecosystem to one dominated by hardwood species will substantially alter forest composition and structure as well as the ecosystem services that this forest provides.

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PART 1

INTRODUCTION

Background

The dispersal, geographic distribution, colonizing success, and mortality of biota in the world has been governed through such functions as climate and topography since the beginning of time, though the ever-increasing dominance of humans in the natural world has recently begun to create a domineering stress on these biota growth categories (Barnes et al. 1998). One significant stress induced on forest ecosystems as a result of human activity is the introduction of exotic insects and pathogens that dramatically alter forest diversity, productivity, and ecosystem function (Barnes et al. 1998).

An excess of 400 exotic insects and 20 exotic fungal pathogens have been introduced into North America since European colonization (Barnes et al. 1998; Foster et al. 2014). Some of these invasive pests are well known by the general public because of the rapid decline in certain revered tree species in North America, including the American chestnut (*Castanea dentata* (Marsh.) Borkh.) by the chestnut blight (*Cryphonectria parasitica* (Murr.) Bar.) and ash species (*Fraxinus* spp. (L.)) by the emerald ash borer (*Agrilus planipennis* Fairmaire) (Lovett et al. 2006). The range-wide decline of these species has been possible because these tree species did not have the evolutionary defenses to respond to exotic pests, and because of this the exotic pest populations were able to flourish unperturbed (Foster et al. 2014). The loss of tree species has profound short-term and long-term effects on forest ecosystems. Short-term effects include a reduction in photosynthesis, changes in light conditions, and increased leaching of nutrients into the soil, and the long-term effects include changes in forest composition, successional trajectories, nutrient uptake, and wildlife habitat (Lovett et al. 2006).

Another important tree species at risk of demise from an invasive insect is eastern hemlock (*Tsuga canadensis* (L.) Carr.; hemlock), a coniferous tree species native to a large portion of the eastern United States (Kirkman et al. 2007). Hemlock is unlike any other conifer in the eastern United States in that it is very shade tolerant, slow growing, and it serves as a foundation species in an area of the country otherwise dominated by deciduous tree species (Foster et al. 2014). Hemlock is currently under threat from the hemlock woolly adelgid (*Adelges tsugae* Annand; HWA), an invasive insect from Japan that is inducing widespread hemlock mortality throughout the range of hemlock (Ward et al. 2004). The southernmost populations of hemlock occur as areas of refugia along the Appalachian Plateau in northwestern and central Alabama (Hart & Shankman 2005), though these populations have not yet been impacted by HWA (Figure 1.1).

Ecology of Hemlock

Hemlock is a native coniferous tree found in all Canadian provinces eastward from Ontario and in all states eastward from Minnesota and north of Florida (Nelson et al. 2014). It is commonly found in mountainous regions on moist upland sites and along lower slopes, streams, ravines, and rocky gorges (Kirkman et al. 2007). Though it can be found in pure stands, it is commonly found within mixed-mesophytic ecosystem types. Hemlock can grow to 60-90 feet tall, and is characterized by slender twigs with leaves of short evergreen needles, cinnamon-brown bark that becomes scaly with age, and small brown cones (Kirkman et al. 2007).

Because hemlock wood is soft, brittle, and coarse-grained, it is not a valuable timber species, although it was heavily harvested in Colonial times for the tannin in its bark (Kirkman et al. 2007). Today, however, the importance of hemlock lies in its value as a foundation species that promotes landscape biodiversity in an area of the country otherwise dominated by deciduous tree species. Hemlock is a very shade tolerant tree species that can persist in the understory of a forest for decades until it is released from suppression (Ward et al. 2004). Once established, hemlock stands create a unique microclimate beneath their thick layers of needles, and they can restrict light levels on the forest floor to only 1% of that above the canopy (Foster et al. 2014). Because of this dense shade, temperatures in the understory of a hemlock forest can be twenty degrees cooler than that of the surrounding area (Foster et al. 2014). Dense shade, little direct snow or rain on the forest floor, a duff layer of needles more than a foot deep, and acidic soils characterize the microclimate beneath hemlock (Foster et al. 2014). Hemlock ecosystems effectively cool stream waters, provide habitat required for a diverse array of hemlock-specialized insects and birds, and provide shelter and food for many animals. Red-backed salamander (*Plethodon cinereus* Green), black-throated green warbler (*Setophaga virens* Gmelin), Acadian flycatcher (*Empidonax virescens* Vieillot), porcupine (*Erethizon dorsatum* L.), snowshoe hare (*Lepus americanus* Erxleben), white-tailed deer (*Odocoileus virginianus* Zimm.), and brook trout (*Salvelinus fontinalis* Mitchill) are a few of the animal species that depend on hemlocks (Ward et al. 2004). There is no other tree species in eastern North America that serves as many functions as hemlock does (Foster et al. 2014).

In the South, hemlock stands are found mostly in the southern Appalachian Mountains, varying in density from isolated individual trees to small pure stands (Kirkman et al. 2007). Hemlock appears to have expanded its range from the northeastern United States into the southern Appalachian Plateau during the late Pleistocene (Hart & Shankman 2005). When the climate warmed during the early Holocene, however, hemlock experienced a southern range contraction. This contraction left areas of refugia for hemlock in the South where hemlock became restricted to cool microclimates (Hart & Shankman 2005). The southernmost populations of hemlock occur as areas of refugia along the Appalachian Plateau in northwestern and central Alabama (Hart & Shankman 2005). These populations can be characterized as disjunct because they are isolated from the main range of hemlock, which begins its southern point in northern Georgia.

Hemlock Woolly Adelgid

HWA is a small insect native to Japan that was first found on ornamental Japanese hemlock (*Tsuga sieboldii* Carr.) in Richmond, Virginia in 1951 (Ward et al. 2004). Eastern hemlock along with Carolina hemlock (*Tsuga caroliniana* Engelm.) is currently being decimated by HWA, of which these two hemlock species have no natural defenses (Ward et al. 2004).

HWA has four distinct lineages in Asia: one in mainland China, one in Taiwan, and two in Japan (Havill et al. 2014). Another lineage of HWA is native to western North America, though the lineage that has spread in eastern North America is specifically from the HWA genotype from southern Japan (Havill et al. 2014). HWA infestations in eastern hemlock occurred at low levels at first and were largely undetected, though the pest has spread prolifically in recent years, inducing catastrophic hemlock mortality from northeastern Georgia to southeastern Maine (Ward et al. 2004). The nymphs of HWA insert their stylets into the base of hemlock needles and feed off of the tree’s starch reserves, and the tree ultimately dies (Foster et al. 2014). HWA infects hemlocks regardless of tree size, age, or condition (Foster et al. 2014), and trees generally die within 2-12 years from the initial infestation date (Ward et al. 2004).

HWA is a member of the family Adelgidae, and it is closely related to true aphids in the family Aphididae (Havill et al. 2014). Both of these families exhibit complex life cycles including both sexual and asexual reproduction, though members of the Adelgidae family are unique in the fact that they are oviparous and typically uses conifer genera as hosts (Havill et al. 2014). In its native range of southern Japan, HWA reproduces sexually on its primary host of tiger-tail spruce (*Picea torano* (Siebold ex K.Koch) Koehne) and asexually on its secondary host of Japanese hemlock (Havill et al. 2014). In eastern North America, this spruce is not found and the HWA population is entirely female and reproduces asexually on hemlock through parthenogenesis (Foster et al. 2014).

HWA completes two asexual generations per year in eastern North America, one in winter (sistens) and one in spring (progrediens) (Ward et al. 2004). Though predominantly wingless, HWA produces winged sexuparae to perform sexual reproduction, though these sexuparae ultimately die in eastern North America in their attempt to find a tiger-tail spruce (Havill et al. 2014). A generation begins when unmated females deposit their ovisacs, which usually contain around 300 eggs each (McClure 1989). The eggs of the progrediens generation hatch in April to May, developing into mobile crawler nymphs that insert stylets into the base of hemlock needles, feeding off the xylem ray parenchyma cells in hemlock twigs (Ward et al. 2004). These nymphs become adults in early June after they have progressed through four nymphal stages, and adults lay eggs in mid-June to begin the sistens generation (Ward et al. 2004).

The eggs of the sistens generation hatch in mid-July, producing crawler nymphs that estivate on the new shoots of hemlock from July through October, producing a woolly wax substance to protect themselves from predation and desiccation (Ward et al. 2004). Nymphs break dormancy in late October as temperatures cool, developing into three subsequent nymphal stages throughout winter (Ward et al. 2004). Nymphs feed during the above freezing periods of winter and early spring (Foster et al. 2014). In early spring, nymphs become adults, completing the two-generation per year life cycle of HWA (Ward et al. 2004).

The eggs and crawlers of both the sistens and progrediens generations are easily transported by wind, birds, and humans (Ward et al. 2004). Migratory birds are known to be major vectors in long-distance dispersal of HWA, and one study found that nineteen out of twenty-two bird species exiting a hemlock forest infested with HWA carried the pest on their bodies (Foster et al. 2014). HWA has been found to spread at an average rate of 12.5 kilometers per year since 1990 (Evans & Gregoire 2007), although its rate of spread northward is limited by temperatures below -25°C, which is the coldest temperature the pest can endure (Foster et al. 2014). Increasingly warm winters in eastern North America, along with evidence that HWA is adapting to the cold, makes the spread of HWA northward into Canada more likely in the near future (Foster et al. 2014).

Mortality is the ultimate fate of a hemlock infested with HWA, though characteristic infestation symptoms include discoloration, desiccation, needle loss, and branch dieback (Havill et al. 2014). Although it is mainly thought that the depletion of the tree's starch reserves by HWA feeding kills hemlock, there is debate over exactly how hemlock mortality is induced (Foster et al. 2014). Many believe that in addition to nutrient depletion, HWA secretes toxic saliva that induces local cell death in hemlock twigs, and hemlock also induce its own local cell death around feeding HWA in a defensive effort to starve the pest (Foster et al. 2014). Though local cell death and nutrient depletion on a single twig may cause nominal damage to the tree, the quick proliferation of thousands of adelgids on a single tree is enough to kill a hemlock in 2-12 years from the initial infestation date (Ward et al. 2004).

Research Justification and Objectives

This study has two main objectives: 1) to examine the current composition and structure of a disjunct eastern hemlock ecosystem type in northwestern Alabama at the southern boundary of the range of hemlock, and 2) to model the effects of possible eastern hemlock mortality from HWA infestation in this area using the U.S.D.A. Forest Service Forest Vegetation Simulator (FVS) and Hemlock Woolly Adelgid Event Monitor. Very little literature exists on the current composition and structure of this hemlock forest ecosystem type, and HWA has yet to spread into Alabama. It is unknown if the isolated location of this hemlock ecosystem type will allow it to avoid HWA infestation in the future (Hart & Shankman 2005). Predicting the spread of HWA into the area using FVS will provide an estimate of the year of infestation, as well as estimates of hemlock mortality through reductions in basal area of hemlock after the initial infestation (Trotter et al. 2008).

The importance of my study comes not only from its description of the current composition and structure of this unique forest ecosystem type, but also from the suggested management implications. With the current threat of HWA infestation in northwestern Alabama, the woody plant, physiography, and soil data collected in this study will serve as a baseline for future management.

It is well documented that HWA induces widespread hemlock mortality (Krapfl et al. 2011). One study showed that a fifteen-year HWA infestation at the Connecticut College Arboretum resulted in a 70% decrease in the basal area of overstory hemlock trees and an 80% reduction in hemlock stem density (Small et al. 2005). Research on the impact of HWA in the mid-Atlantic and New England areas has been extensive, while little research has been conducted on the insect's impact in the extreme southern part of the range of hemlock (Krapfl et al. 2011). In New England, it was found that major changes in forest ecosystem composition and structure ensue after HWA infestation. One study found that after the hemlocks died, soil moisture declined rapidly and streams once shaded by the trees experience increased water temperatures (Foster et al. 2014). Species such as black birch (*Betula lenta* L.) and red maple (*Acer rubrum* L.) also began to colonize the understory, and a notable increase in the numbers of large ants from the genera *Camponotus, Formica, and Lasius*, were seen after the hemlocks were killed (Foster et al. 2014). In the South, in one notable study that was performed on the ecosystem impacts of HWA it was found that in the Great Smoky Mountains National Park, the majority of hemlocks had been infected and were in a serious state of decline. It was predicted that hemlock would disappear from the southern Appalachians, and the widespread presence of great laurel (*Rhododendron maximum* L.) in the understory of infested stands indicates the potential for this shrub species to drive successional patterns once hemlock is extirpated (Krapfl et al. 2011). Other studies support the hypothesis that great laurel and (or) yellow-poplar (*Liriodendron tulipifera* L.) are the likely candidates to replace hemlock in the southern Appalachians (Ellison et al. 2005). It was also noted that further research is needed to predict the extirpation of hemlock and subsequent forest successional trajectories in the southern Appalachians (Krapfl et al. 2011).

In addition to developing an understanding of the current composition and structure of a disjunct hemlock ecosystem type in northwestern Alabama, my study entails modeling a potential infestation by HWA using the U.S.D.A. Forest Service FVS and the Hemlock Woolly Adelgid Event Monitor. This computer model simulates ecological processes using mathematical and statistical calculations (Foster et al. 2014). One study that used the FVS Southern Variant found that there would be an almost complete loss of hemlock in southeastern Kentucky once HWA infested the area. It was predicted that less than 2% of hemlock basal area would survive 20 years after infestation, and the forest would soon convert to forest types dominated by oak (*Quercus* spp. L.), hickory (*Carya* spp. Nutt.), and yellow-poplar (Spaulding & Rieske 2010). However, there has been very little research on forest response to HWA infestation in forests at the edge of the range of hemlock (Macy 2012).

Given the current situation, management alternatives for the control of HWA spread and the forestry implications post-infestation need to be carefully considered. As noted above, very little research has been conducted on the management implications of HWA infestation on hemlock forest ecosystem types in northwestern Alabama and the surrounding region. My study will serve to provide baseline information to guide future HWA mitigation measures in an effort to promote the survival and viability of hemlock in the region.

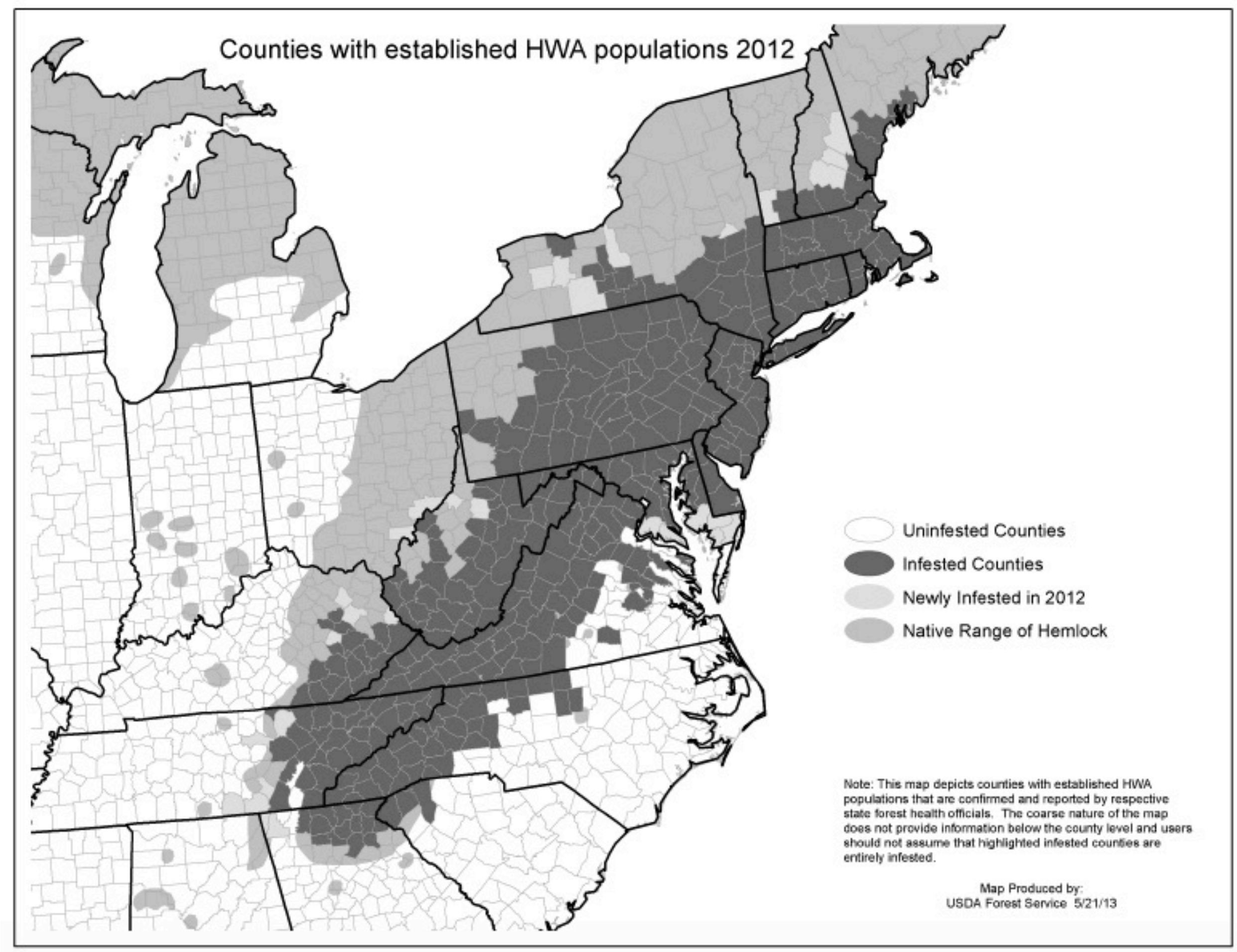

Figure 1.1. HWA distribution within the native range of hemlock as of 2012. Source: U.S.D.A. Forest Service (2013).

PART 2

CURRENT COMPOSITION AND STRUCTURE OF A DISJUNCT EASTERN HEMLOCK ECOSYSTEM IN NORTHWESTERN ALABAMA

Introduction

A foundation species is a species that defines the composition and structure of an ecosystem by influencing major ecosystem processes and by creating a stable system needed for the viability of other species in the area (Ellison et al. 2005). Eastern hemlock represents a foundation species through its characteristics as a late-successional species that is slow growing and very shade tolerant. Hemlock needles restrict light levels reaching the forest floor, are slow to decompose, and contribute to soil acidification that creates a soil environment with low rates of nitrogen mineralization and nitrogen fixation (Lovett et al. 2006).These characteristics of hemlock can contribute to ecosystem-level effects that can restrict the amount and variety of other plant species a hemlock forest will support, cool stream waters that flow through the forest, and provide habitat for wildlife species such as white-tailed deer (*Odocoileus virginianus* Zimm.) and the black-throated green warbler (*Dendroica virens* Gmelin) (Lovett et al. 2006).

While it is clear that hemlock plays a pivotal role in forest ecosystem health, diversity, and stability, few studies (i.e.. Hardin & Lewis 1980; Hart & Shankman 2005) have provided a comprehensive analysis of the ecosystem components of a hemlock-dominated forest at the southern boundary of the hemlock's range, and in particular at disjunct locations in Alabama. Hemlock was first discovered in Alabama in the early 20th century in the northwestern part of the state. It was found to be restricted to slopes along tributaries of the Warrior River and in sandstone gorges and ravines (Harper 1943; Segars et al. 1951). In one study by Hart &

Shankman (2005), the reproductive viability of hemlock-dominated forests in Alabama was studied, and it was found that the dominant presence of small hemlock trees in the understory of these forests implied a self-replacing, viable population. In another study by Hardin & Lewis (1980), a forest in Alabama was found to be dominated by hemlock and American beech (*Fagus grandifolia* Ehrh.), and the soils in the area were characterized as acidic sandy loams.

While these studies by Hart & Shankman (2005) and by Hardin & Lewis (1980) provide an initial view of the composition and structure of hemlock-dominated forests in Alabama, the comprehensive examination that my study entails is needed given the current threat of an HWA infestation in the area. HWA infestation in hemlock forests has been documented to induce hemlock mortality upwards of 95% (Orwig & Foster 1998), and the cascading effects of this mortality on forest dynamics will alter the composition and structure of present-day hemlock forests in Alabama. My study provides one of the last opportunities to examine the unique composition and structure of a disjunct hemlock ecosystem type in Alabama before it is most likely permanently altered by HWA.

Study Area

Plot sampling was conducted on the William B. Bankhead National Forest in northwestern Alabama. William B. Bankhead National Forest was established in 1918. It was estimated that approximately 40% of the land was cut over for farmland, although uncut forest still existed on public domain land and in deep gorges (U.S.D.A. Forest Service 2015). William B. Bankhead National Forest is now almost entirely forest and includes the Sipsey Wilderness Area and the Sipsey Fork, which are the largest national forest wilderness area east of the

Mississippi and the only National Wild and Scenic River in Alabama, respectively (U.S.D.A. Forest Service 2015). The major forest community types in this forest are upland hardwood and hardwood pine mixture, while riparian areas are dominated by hemlock (Chen & Fraser 2009; Powers et al. 2003). The area is within the Southwestern Appalachians zone of Alabama physiography and the forest is laced with streams of moderate gradients with sand, sandstone, and shale bedrock substrata (Chen & Fraser 2009; Powers et al. 2003).

Methods

Woody Plant Inventory

Ten 200-m^2 circular plots were established in an eastern hemlock-dominated forest ecosystem type (Figure 2.1; Figure 2.2). To establish the general plot locations, geospatial data provided by the U.S.D.A. Forest Service was used. The vector data pertaining to forest cover types, trails, and roads in the Bankhead National Forest were downloaded into QGIS version 2.6.1-Brighton in order to delineate plot locations. The two forest cover types that contain the eastern hemlock ecosystem type (i.e., hemlock-dominated stands), indicated with Common Stand Exam FSHR8 Existing Vegetation Codes, are hemlock-hardwood (8) and cove hardwood-white pine-hemlock (41). One 120-m transect with five 200-m^2 plots were delineated in each forest cover type, creating a total sample area of 0.2 hectares. Systematic random sampling procedures available on QGIS were employed to randomly locate the first plot center for each transect, and the next four plot centers were located 30 m from each other along the transect. Systematic random sampling was employed because hemlock ecosystem types in Alabama are known to be restricted to north and east facing slopes parallel to permanent watercourses (Hart & Shankman

2005). Systematic random sampling, along with the use of circular plots instead of square plots, makes sampling units easier to locate on the ground and sampling feasible to be performed by one person (Avery & Burkhart 2001).

To locate the first plot on each transect and to measure distances between plots, a compass and Keson tape, respectively, were used. Within each plot, a metal stake was used to delineate the center point and the radius of the plot was measured using the Keson tape. For a 200-m^2 circular plot, the plot radius was 7.98 m. To correct for slope, the following equation (Avery & Burkhart 2001) was used:

$$Radius\ (m) = \frac{uncorrected\ plot\ radius}{\cos(\ slope\ angle\ in\ degrees)}$$

Within each plot, all woody plants with diameters at breast height (DBHs) of 2.5 cm and greater were inventoried by species and by DBH. Stems between 2.5 cm and 10.0 cm were classified as large saplings, while stems greater than 10.0 cm were classified as trees. In addition to species and DBH, the crown class (dominant, codominant, intermediate, or overtopped) (Smith et al. 1997) of each tree was determined. DBH is defined as the stem diameter outside bark at 1.3 m above the ground (Avery & Burkhart 2001), and it was measured using a D-tape. Woody plants with stems less than 2.5 cm DBH but with heights greater than or equal to 1 m (confirmed with a meter stick) were categorized as small saplings, and small saplings were inventoried using a dot tally by species. Woody plants smaller than 1 m in height were categorized as seedlings. Because of time constraints, only seedlings rooted within an 8-m^2 nested plot (5% of the total plot area) centered on the 200-m^2 plot center (Figure 2.1) were inventoried with a dot tally by species, and these nested plots were also corrected for slope.

These methods are based on those from a study performed in eastern hemlock ecosystems in southeastern Ohio (Martin & Goebel 2013).

The relative density of each species in the seedlings, small saplings, large saplings, and trees size categories were then calculated. For trees, the relative dominance and importance value of each species were also calculated. Shannon-Weiner Index values (Barnes et al. 1998), Simpson's Index values (Barnes et al. 1998), and evenness values (Pielou's J) (Pielou 1969) were calculated for each woody plant size class. The formulas involved in these calculations are as follows:

$$Relative\ density\ (\%) = \frac{number\ of\ a\ species}{total\ number\ of\ all\ species} \times 100$$

$$Relative\ dominancy\ (\%) = \frac{basal\ area\ of\ a\ species}{total\ basal\ area\ of\ all\ species} \times 100$$

$$Importance\ value\ (\%) = \frac{relative\ density + relative\ dominance}{2} \times 100$$

$$H' = -\sum_{i=1}^{S} p_i \ln{(p_i)}$$

$$E = \frac{H'}{H'max} = \frac{H'}{\ln S}$$

$$D = -\sum_{i=1}^{S} \frac{n_i(n_i - 1)}{N(N-1)}$$

Where *basal area*= 0.00007854(DBH)^2, H'= Shannon-Weiner index, S= number of species in the sample, p_i= proportion of individuals that are in species i, E= Pielou's J, $H'\ max$= maximum value of H', D= Simpson's index, n_i= number of individuals in species i, and N= total number of species in the sample (Barnes et al. 1998).

Physiography

The landform, percent slope, aspect, slope (topographic) position, and slope shape were recorded at each plot center. Landform can be described as hillslope, plateau, outwash plain, or river floodplain (Barnes et al. 1998). Percent slope was measured using a clinometer and the aspect (azimuth in degrees) was measured using a compass. Slope (topographic) position is described as ridgetop, upper slope, middle slope, lower slope, or bottom, while slope shape is described as convex, concave, or linear (Barnes et al. 1998). The latitude and longitude of each plot center was recorded using a Garmin GPSMAP 64 handheld GPS device.

Soil

The U.S.D.A. Web Soil Survey was employed to distinguish the soil series present at each plot location. To confirm the soil textures of the given soil series and to document specific soil attributes for the plots in this study, a soil sample was taken near each plot center. To take each sample, the O-horizon was removed by hand and approximately 50 grams of soil from the A-horizon was placed in a plastic container for later analysis. Each sample was tested for soil pH using a Hellige-Truog soil pH test kit (Hellige, Inc., Garden City, NY). Each sample was also tested for soil texture using the soil texture by feel method (Thien 1979).

Results

Woody Plant Species Composition and Structure

Hemlock dominated the overstory with the largest IV (49%) of the eleven tree species found (Table 2.1). The second most important tree species came from the combined IV of 36% from oak, which included chestnut oak (*Quercus montana* L.; 23% IV), white oak (*Quercus alba* L.; 9% IV), and scarlet oak (*Quercus coccinea* L.; 4% IV). Loblolly pine (*Pinus taeda* L.) was also important and had an IV of 8%. A total of 156 trees were inventoried, the largest tree inventoried was a hemlock with a DBH of 67 cm, and the majority of hemlock in the overstory were in the codominant or intermediate crown classes (Appendix A).

The large sapling size class was characterized by the presence of twelve woody plant species, and hemlock dominated this size class with a relative density of 49% (Table 2.2). Mountain laurel (*Kalmia latifolia* L.) and eastern hophornbeam (*Ostrya virginiana* (Mill.) Koch) were also important species in this size class with relative densities of 18% and 13%, respectively. The other nine woody plant species in the large saplings size class had low relative densities of 1-3%; e.g., red maple (*Acer rubrum* L.), American beech (*Fagus grandifolia* Ehrh.), and American holly (*Ilex opaca* Aiton). A total of 71 large sapling size-class stems were inventoried, and 35 of these stems were hemlock (Appendix B).

The small saplings size class was dominated by American holly and bigleaf magnolia (*Magnolia macrophylla* Michx.), both of which had relative densities of 22% (Table 2.3). Hemlock had the third highest relative density (19%), while red maple and mountain laurel both had relative densities of 11%. A total of eight woody plant species with 27 total stems were found in the small sapling size-class (Appendix C).

The seedlings size class included twelve woody plant species with a total of 222 stems counted in the ten 8-m^2 nested plots (Appendix D). Chestnut oak and red maple dominated this size class with relative densities of 45% and 25%, respectively (Table 2.4). Oak (i.e., chestnut oak, white oak, and scarlet oak) had a combined relative density of 53%, while hemlock had one of the lowest relative densities (1%), with only two hemlock seedling stems inventoried.

The Shannon-Weiner Index diversity values for the trees, large saplings, small saplings, and seedlings varied from 1.4-1.9, with trees having the smallest value and seedlings having the largest (Figure 2.3). Simpson's Index for diversity varied from 0.1-0.4 for the four size classes, with small saplings having the smallest value and trees having the largest. Evenness as represented by Pielou's J varied from 0.6-0.9, with trees achieving the smallest value and small saplings achieving the largest.

Physiography

The physiography of the study area can be characterized by steep north-facing hillslopes. The average slope steepness of the plots was 26% with a range of 20-30% (Table 2.5). Aspect (degrees in azimuth) ranged from 340°-10°, while seven of the plots were in the midslope position, two were lower slope, and one was upper slope. The slope shape of the plots included concave (4 plots), convex (3 plots), and linear (3 plots) slopes.

Soil

All ten samples of the A-horizon of the plots were classified at loamy sand (Table 2.6). The sampled A-horizons were all acidic, i.e., pH averaged 5.0 with a range from 4.5-6.0. All ten plots were found to fall within the soil map unit of Muskingum stony fine sandy loam, steep phase (Mg) (Soil Survey Staff 2015).

Discussion

Hemlock was found to be the dominant tree species in the study area, which is expected of a foundation species that is locally abundant and which has a stabilizing effect on ecosystem functions (Ellison et al. 2005). It was also expected that oak species such as chestnut oak and white oak were the other dominant tree species, as these species have been documented to be associated with hemlock in the South (Bormann & Platt 1958).

In their study of the composition and structure of disjunct hemlock stands in Alabama similar to the one in my study, Hart & Shankman (2005) discovered that the major understory plants species in this forest ecosystem type included American holly, mountain laurel, and bigleaf magnolia. This is similar to the results of my study, in which I found these these species to be most common in the large and small saplings size-classes. Bormann & Platt (1958) and Hart & Shankman (2005) also found that the hemlock-dominated ecosystem type in this area is almost exclusively restricted to steep, north-facing slopes with acidic soils. It was therefore expected that my study area would have these physiographic conditions and acidic soil. The presence of loblolly pine (8% IV) in the overstory provided a stark contrast to hemlock, as these two species occupy opposing positions in forest succession and shade tolerance. Loblolly pine is known to occupy small openings in hardwood forests, and because the loblolly pine trees found were present as lone trees rather than in groups, this is most likely why loblolly pine was present in the study area (Kirkman et al. 2007).

It is interesting to note the lack of hemlock stems in the small sapling and seedlings size-classes. Hart & Shankman (2005) noted that disjunct hemlock stands in Alabama in their study had abundant hemlock seedlings, and the number of hemlock stems generally decreased with each increasing size class of hemlock. This is in contrast to my study, as hemlock had a relative density of 60% in the overstory, but only 1% in the seedling size-class. While this may be evidence that the hemlock stands in my study do not appear to be self-replacing, it can also be attributed to the tendency of hemlock to exhibit poor recruitment as a result of deer browsing, low seed viability, and very precise seedbed moisture and temperature requirements (Macy 2012). It is also possible that the stands sampled were in the stem exclusion stage of succession, which is a successional stage characterized by a lack of regeneration (Barnes et al. 1998). To confirm successional stage, however, further analysis into the diameter and age class distributions of the forest need to be performed.

Because Shannon-Weiner Index values generally range from 1.5-4.5 and Simpson's Index is scaled from 0-1 (Barnes et al. 1998), it can be said that the stands sampled were generally low in woody plant diversity. This was to be expected because forests dominated by a foundation species such as hemlock are generally low in diversity, and hemlock-dominated forests are known to exhibit lower species diversity than eastern hardwood forest types (Ellison et al. 2005). The woody plant evenness in the sampled stands can be characterized as moderately even, as Pielou's J ranges from 0-1 (Pielou 1969).

Because the stands sampled were dominated by hemlock in the overstory and by deciduous species in the understory, this area is at risk of major changes in the event of a HWA infestation. It is critical to understand the current composition and structure of this forest ecosystem type if silvicultural options are going to be employed to mitigate the potential for a catastrophic HWA infestation in the future. In a recent interview, Mary Ann Fajvan, a research forester for the U.S.D.A. Forest Service, suggested that there are three potential silvicultural options for managing hemlock forests at risk of an HWA infestation: 1) thinning hemlock through crop tree management, 2) shelterwood cutting, and 3) doing nothing (Abraham 2015). The choice among these strategies is highly dependent on the current composition and structure of the forest in question, and for this reason my study serves as a baseline and as an important historical documentation for a forest ecosystem type at risk of a HWA infestation. Further research that includes an examination of the herbaceous vegetation and wildlife specific to this forest would also be beneficial in gaining greater insight into this unique forest ecosystem type.

Table 2.1. Species, relative densities, relative dominances, and importance values of trees (stems >10.0 cm DBH) inventoried in the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama.

Species	**Relative Density (%)**	**Relative Dominance (%)**	**Importance Value (%)**
Acer rubrum	3	1	2
Carya spp.	2	1	1
Diospyros virginiana	1	0	1
Fagus grandifolia	1	2	2
Liriodendron tulipifera	1	0	1
Magnolia macrophylla	3	1	2
Pinus taeda	3	13	8
Quercus alba	6	11	9
Quercus coccinea	3	5	4
Quercus montana	18	28	23
Tsuga canadensis	60	38	49

Table 2.2. Species, number of stems, and relative densities of large saplings (stems 2.5-10.0 cm DBH) inventoried in the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama.

Species	**Number of Stems**	**Relative Density (%)**
Acer rubrum	2	3
Carya spp.	1	1
Cornus florida	1	1
Fagus grandifolia	2	3
Fraxinus spp.	1	1
Hamamelis virginiana	1	1
Ilex opaca	2	3
Kalmia latifolia	1	18
Magnolia macrophylla	3	4
Ostrya virginiana	9	13
Quercus montana	1	1
Tsuga canadensis	35	49

Table 2.3. Species, number of stems, and relative densities of small saplings (stems < 2.5 cm DBH and ≥ 1m in height) inventoried in the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama.

Species	**Number of Stems**	**Relative Density (%)**
Acer rubrum	3	11
Carya spp.	2	7
Ilex opaca	6	22
Kalmia latifolia	3	11
Magnolia macrophylla	6	22
Quercus montana	1	4
Tsuga canadensis	5	19
Unknown	1	4

Table 2.4. Species, number of stems, and relative densities of seedlings (stems < 1 m in height) inventoried in the ten 8-m^2 nested plots on the William B. Bankhead National Forest in northwestern Alabama.

Species	**Number of Stems**	**Relative Density (%)**
Acer rubrum	56	25
Carya spp.	7	3
Cornus florida	2	1
Kalmia latifolia	7	3
Quercus alba	11	5
Quercus coccinea	6	3
Quercus montana	100	45
Quercus rubra	2	1
Smilax spp.	13	6
Toxicodendron radicans	3	1
Tsuga canadensis	2	1
Unknown	13	6

Table 2.5. Summary of physiography data and coordinates for the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama.

Plot	Landform	Slope (%)	Aspect (degrees in azimuth)	Slope Shape	Slope Position	Latitude	Longitude
1	Hillslope	20	340	Concave	Midslope	N 34 21.372	W 087 16.866
2	Hillslope	25	350	Concave	Midslope	N 34 21.386	W 087 16.855
3	Hillslope	25	345	Convex	Midslope	N 34 21.391	W 087 16.837
4	Hillslope	35	340	Convex	Lower Slope	N 34 21.405	W 087 16.848
5	Hillslope	25	353	Linear	Lower Slope	N 34 21.407	W 087 16.827
6	Hillslope	27	350	Concave	Midslope	N 34 19.033	W 087 28.064
7	Hillslope	24	350	Concave	Midslope	N 34 19.038	W 087 28.043
8	Hillslope	28	354	Convex	Upper Slope	N 34 19.036	W 087 28.030
9	Hillslope	25	6	Linear	Midslope	N 34 19.043	W 087 28.022
10	Hillslope	30	10	Linear	Midslope	N 34 19.051	W 087 28.015

Table 2.6. Summary of A-horizon soil pH, A-horizon soil texture, and soil map units (Soil Survey Staff 2015) of the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama.

Plot	A-Horizon Soil pH	A-Horizon Soil Texture	Soil Map Unit
1	6.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
2	4.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
3	4.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
4	4.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
5	5.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
6	5.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
7	4.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
8	5.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
9	4.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)
10	4.5	Loamy Sand	Muskingum stony fine sandy loam, steep phase (Mg)

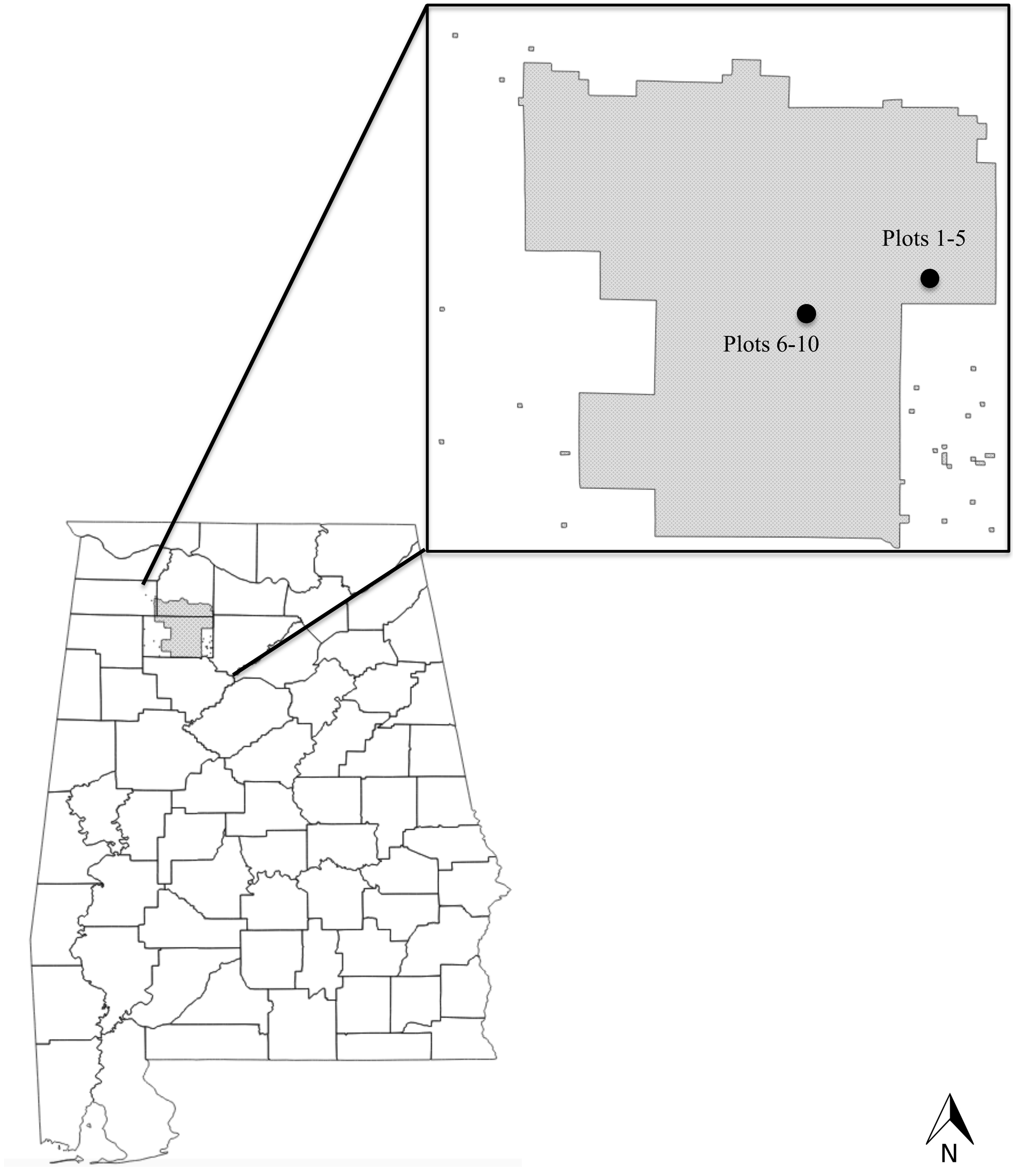

Figure 2.1. Locations of the ten 200-m^2 plots on the William B. Bankhead National Forest (gray area) in northwestern Alabama.

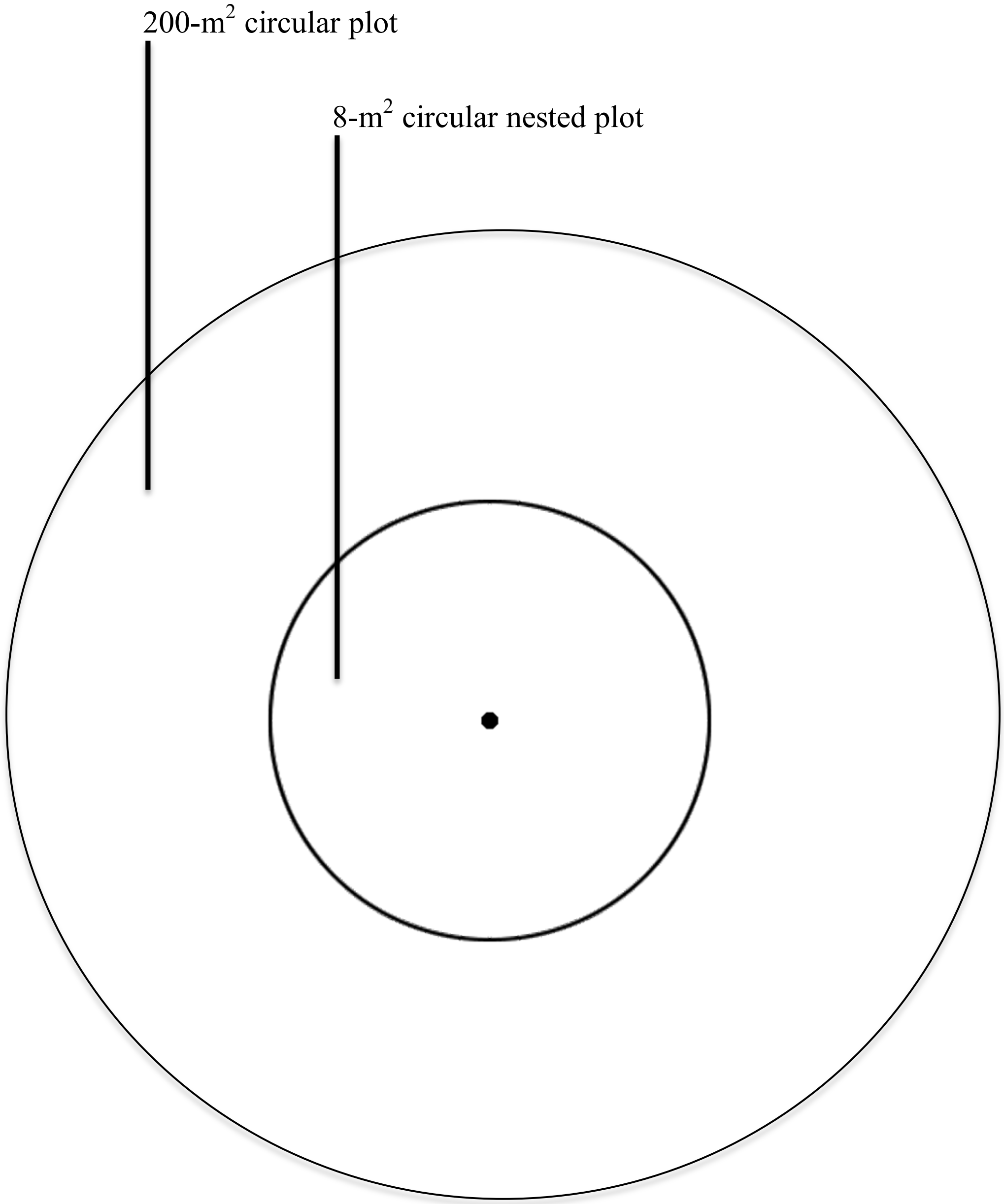

Figure 2.2. Sample plot design of the 200-m^2 circular plot and 8-m^2 circular, nested plot (not to scale).

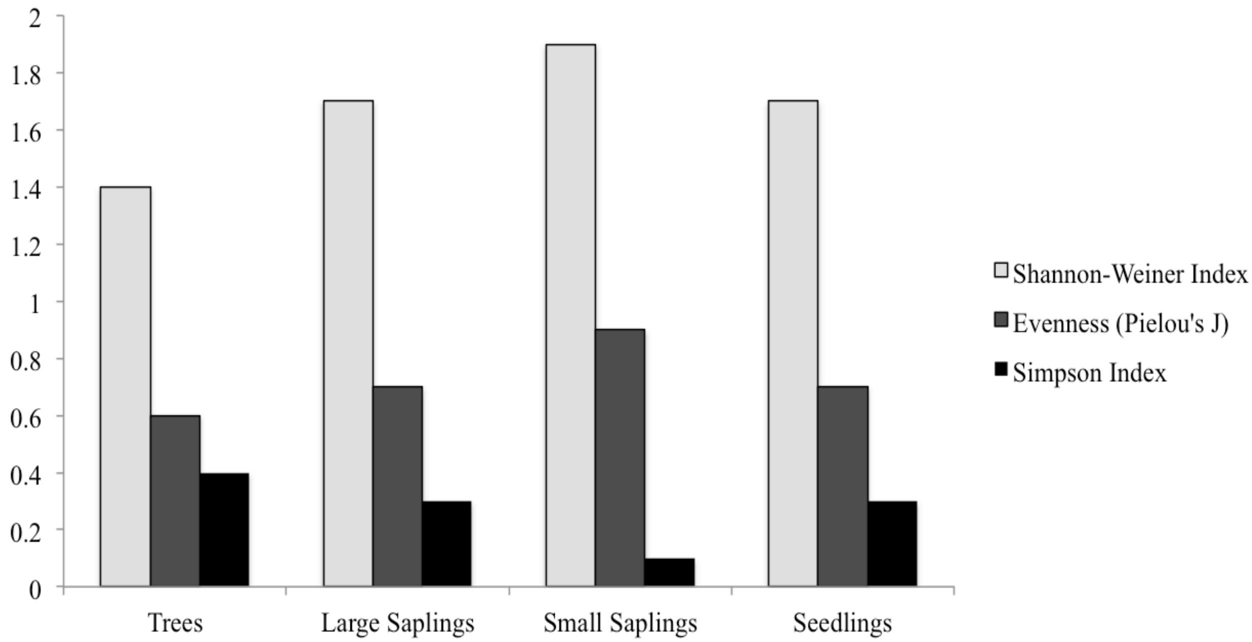

Figure 2.3. Diversity values for the trees, large saplings, small saplings, and seedlings inventoried in the ten 200-m^2 plots (for trees, large saplings, and small saplings) and the ten 8-m^2 nested plots (for seedlings) on the William B. Bankhead National Forest in northwestern Alabama.

PART 3

MODELING POTENTIAL HEMLOCK WOOLLY ADLEGID INFESTATION

Introduction

Hemlock woolly adelgid (*Adelges tsugae* Annand; HWA) is an invasive insect native to Japan that is present in about half of the range of eastern hemlock (*Tsuga canadensis* (L.) Carr.; hemlock) (Havill et al. 2014). HWA is known to induce mortality in hemlock within 2-12 years following initial infestation, and HWA infests hemlock regardless of tree age or size (Ward et al. 2004). HWA has spread almost entirely throughout hemlock's southern range, but has yet to reach disjunct populations of hemlock in Alabama (Havill et al. 2014; U.S.D.A. Forest Service 2013).

Because of hemlock's role as a foundation species and the extensive hemlock mortality HWA is known to induce, there has been recent interest in predicting both HWA infestation and the subsequent forest compositional and structural changes using ecological models (Foster et al. 2014). Ecological models involve functional processes that are simulated using mathematical and statistical calculations, and the Forest Vegetation Simulator (FVS) is a computer software program developed by the U.S.D.A. Forest Service that simulates the development of a forest stand under many conditions, including insect outbreaks (Foster et al. 2014; Avery & Burkhart 2001). FVS operates under geographical variants that utilize tree growth, mortality, and volume equations for a particular geographical region, and the Southern Variant was used for this study because this variant covers all 13 states of the Southern Region, including Alabama (Keyser 2008).

Extension modules are available within FVS that provide a framework to simulate the effects of specific factors on stand development, including insect and pathogen outbreaks, snag dynamics, and fire effects (Dixon 2002). The Hemlock Woolly Adelgid Event Monitor is an FVS extension that predicts the time, trajectory, and intensity of HWA infestations, as well as the subsequent stand development changes that occur after an infestation (Trotter et al. 2008). The HWA Event Monitor is composed of two addfiles (*.kcp files), one for the Northeastern Variant and the other for the Southern Variant. The addfiles require three assumptions pertaining to HWA: 1) time of infestation, 2) intensity of the infestation, and 3) whether the HWA population is cyclical or saturated. In the Southern Variant, it is commonly assumed that HWA populations are saturated, as populations in this region are known to grow so quickly that hemlock is unable to recover (Trotter et al. 2008).

It has been documented that HWA spreads between 12.5 km/year and 15.6 km/year (Evans & Gregoire 2007), and these two rates of spread can be used create “worst” and “best” case scenarios for the times of infestation in stands. The HWA Event Monitor simulates the reduction in hemlock basal area in 5-year cycles, and the intensity of hemlock mortality is determined stochastically based on the following five pre-determined mortality ranges: “no infestation” for 0% loss of hemlock, “low infestation (5-15% loss), “moderate infestation” (15-40% loss), high infestation (40-90% loss), and “catastrophic infestation” (90-100% loss) (Forest Health Technology Enterprise Team (FHTET) 2008). The probability of each of these mortality ranges is based on the following probability distribution for the Southern Variant of FVS: low infestation, 10%; moderate infestation, 30%; high infestation, 30%; and catastrophic infestation, 30%. It is assumed that the HWA population will surge at the beginning of the infestation and promote severe infestations, though HWA populations will reach an upper limit and then decline once there are not enough hemlock to support a large HWA population. This characteristic of HWA population dynamics forces an attenuated rate of hemlock mortality; a “no infestation” scenario cannot occur once a stand is infested, and a catastrophic infestation only occurs once in the simulation run (Forest Health Technology Enterprise Team (FHTET) 2008).

Macy (2012) used the HWA Event Monitor Northeastern Variant and predicted that HWA would infest the Huron-Erie Lake Plain and Glaciated Allegheny Plateau physiographic regions of northeastern Ohio in 2027 and 2028, respectively. The study also predicted a loss of hemlock basal area of up to 80% in this area thirty years after the initial infestation. Another study that used the Southern Variant found that there would be an almost complete loss of hemlock in southeastern Kentucky once HWA infested the area (Spaulding & Rieske 2010). It was predicted that less than 2% of hemlock basal area was to survive 20 years after infestation, and the forest would soon convert to hardwood forest types of oak (*Quercus* spp. L.), hickory (*Carya* spp. Nutt.), and yellow-poplar (*Liriodendron tulipifera* L.) However, there has been very little research on forest response to HWA infestation in forests at the edge of hemlock’s range (Macy 2012). My objective was to model the effects of possible hemlock mortality from HWA infestation at the southern boundary of the hemlock’s range in northwestern Alabama by using the two rates of spread for HWA and relating these rates to the nearest infested county.

Methods

Woody Plant Inventory

The ten 200-m^2 plots previously established on the William B. Bankhead National Forest in northwestern Alabama were used to acquire the plot-level data needed to run the FVS simulations. The inventory data collected for the trees and large saplings in each of the plots was used in the simulations. Trees were defined as stems greater than 10.0 cm DBH and large saplings were classified as stems between 2.5 and 10.0 cm DBH, and trees and saplings were inventoried by species and DBH (Appendices A and B). DBH is defined as the stem diameter outside bark at 1.3 m above the ground (Avery & Burkhart 2001), and it was measured using a D-tape.

Forest Vegetation Simulator

In order to simulate an HWA infestation in the study area using FVS and the HWA Event Monitor, two potential infestation dates were estimated. The latitude and longitude of each plot center was recorded using a Garmin GPSMAP 64 handheld GPS device. The latitudes and longitudes of all ten plots (Table 2.5) were averaged to acquire a geographic centroid of 34° 20' 2.162" N 87° 13' 27.8652" W. The distance from this geographic centroid to the nearest HWA-infested county (Franklin County, Tennessee) was then used to estimate years of initial infestation by dividing the distance by the known spread rate of HWA. It has been documented that HWA spreads between 12.5 km/year and 15.6 km/year (Evans & Gregoire 2007), and these two rates of spread were used create a "worst" and "best" case scenario for the times of infestation in the stands studied in Alabama.

The vegetation data gathered from the tree and large saplings inventories were then entered into the Microsoft Access database that comes with downloading the HWA Event Monitor. The data was then run through FVS simulations to predict forest growth at 5-year intervals starting with each infestation year and ending in 2080. The FVS Southern Variant and the Bankhead National Forest growth models were used in the simulations. A control simulation was first run in which forest growth was simulated with the same parameters, but without the influence of a HWA infestation. Two simulations were run for each infestation date: one control simulation and one with HWA-induced mortality. FVS-generated hemlock basal area and basal area of all species was recorded at each 5-year interval, and the four most common tree species groups (% of all trees per hectare) as estimated by FVS for 2015 and 2080 were recorded for each simulation.

Results

The "best" and "worst" case FVS scenarios using the two HWA rates of spread indicated that HWA will infest the study area between 2024 and 2027. FVS simulations using the HWA Event Monitor predict that major changes in hemlock basal area and forest species composition will occur in the wake of infestation, and reduction in hemlock basal area of >99% by the year 2060 is forecasted for both infestation dates of 2024 and 2027.

In the FVS simulation with a 2024 infestation date, hemlock basal area is forecasted to remain at a stable 19 m^2/ha, or about 42% of total basal area, before the infestation (Table 3.1; Figure 3.1). By the year 2025, however, hemlock basal area is predicted to decline drastically to only 5 m^2/ha following the catastrophic HWA infestation. All hemlock is forecasted to die in the study area by the year 2035, and though total basal area of the study area is predicted to decline initially in the wake of an infestation from 43 m^2/ha in 2015 to a low of 30 m^2/ha in 2040, it is expected to increase to 43 m^2/ha by 2080. The top four tree species groups (as a percentage of total trees per hectare) in 2080 are predicted to be chestnut oak (30%), white oak (11%), other hardwoods (9%), and eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch; 8%) (Table 3.2).

Catastrophic infestation is also forecast to occur when the 2027 infestation date is used with the FVS. Hemlock basal area is forecasted to increase slightly from 18 m^2/ha in 2015 to 21 m^2/ha just before the infestation, then hemlock basal area is predicted to decline to 16 m^2/ha by 2030 and to 0 m^2/ha by 2045 (Table 3.3; Figure 3.2). Total basal area of the study area is expected to decline initially from 43 m^2/ha in 2015 to a low of 28 m^2/ha in 2040, and then total basal area is expected to increase to 40 m^2/ha by 2080. The top four tree species groups (as a percentage of total trees per hectare) in the year 2080 are forecasted to be chestnut oak (31%), white oak (11%), loblolly pine (8%), and other hardwoods (8%) (Table 3.4).

In both simulations of the control stands where forest development was modeled without HWA-induced mortality, hemlock basal area was predicted to increase from 18 m^2/ha in 2015 to 31 m^2/ha in 2080, increasing from about 42% to 63% of the total basal area of the study area (Table 3.1; Table 3.2; Figure 3.3; Figure 3.4). Total basal area is expected to increase from 43 m^2/ha in 2015 to 49 m^2/ha in 2080. In 2080, the top four tree species groups (as a percentage of trees per hectare) are expected to be hemlock (81%), chestnut oak (6%), loblolly pine (3%), and American beech (*Fagus grandifolia* Ehrh.; 3%) (Table 3.5; Table 3.6).

Discussion

Significant reductions in hemlock basal area immediately after an HWA infestation are forecast, and with an almost complete extirpation of hemlock in the area by the year 2060. This complete mortality of the tree species that makes up nearly 50% of the current overstory composition will cause major changes in forest functional processes, including changes in nutrient cycling, biodiversity, hydrology, and wildlife (Ellison et al. 2005).

There are, however, limitations inherent in modeling using FVS and the HWA Event Monitor. The HWA Event Monitor was developed based on studies of HWA population dynamics in the Northeast (Trotter et al. 2008), and the two rates of HWA spread as published by Evans & Gregoire (2007) are generalized for the Northeastern and Southeastern United States. The hemlock stands I studied were located at the extreme southwestern edge of hemlock's range and were present at disjunct locations, and these unique geographic characteristics were not factored into the rate of spread used in the FVS simulation. It is possible that the isolation of Alabama's hemlocks would keep HWA at bay for longer than I have predicted, although it is likely that once HWA infest the area, hemlock would suffer significant mortality as FVS has forecast.

In addition to the above aspects of HWA population dynamics that could not be factored into the simulation, there are also certain ecosystem components that could not be modeled. The HWA Event Monitor predicts forest development only in the absence of any forest management activities, and any specific prediction of regeneration is limited because the dormant seed bank and variations in individual tree mortality cannot be factored into the simulation. It was also not possible to factor in the potential effects of humans into FVS. The majority of land around the study area is agricultural, and the isolation of hemlock stands in Alabama limits how often humans are in contact with these hemlock forests, which likely will influence the date of the initial HWA infestation.

Even with these modeling limitations, it is important to note the significant consequences HWA infestation will have on the health of Alabama's hemlock forests. In Alabama, hemlock is largely restricted to cool riparian areas along permanent watercourses (Hart & Shankman 2005). Hemlock often provides direct shade to waterways in Alabama, and because hemlock needles can restrict light levels to only 1% of that above the canopy (Foster et al. 2014), these waterways are cooled significantly because of hemlock. When these hemlocks die and are replaced by deciduous species that have lighter leaf pigments and are leafless throughout winter, water temperatures will likely rise. Warm water holds less dissolved oxygen than cold water, and along with the excess organic matter entering streams from decaying hemlocks and deciduous leaf litter, this can create eutrophic conditions that will impair both water quality and aquatic life (USGS 2015). The canopy gaps created by hemlock mortality will also offer micro-sites for invasive species such as kudzu (*Pueraria* spp. DC.) and ailanthus (*Ailanthus altissima* (Mill.) Swingle), and the suite of wildlife species that depend on hemlock will be strained and potentially eliminated from the area (Ellison et al. 2005).

Though Alabama's hemlock forests are isolated, hemlock mortality from HWA will have a cascade of consequences on the ecosystem services these forests will provide in the future. Eutrophication of waterways can impair drinking water reserves and fishing opportunities, deer populations and subsequent hunting opportunities in the area may be reduced, and the hazard of hemlock snags can prompt trail closures in popular recreational areas. The decomposition of dead and dying hemlocks can also reduce the area's ability to act as a long-term carbon sink, and this could reduce the economic returns for the local economy from the growing carbon market. The elimination of hemlock may also make the area less resilient to the effects of climate change as it will represent a major loss of landscape biodiversity.

Management Implications

HWA control mechanisms at the forest level are not currently available (Ward et al. 2004), although silvicultural options have been suggested to mitigate the insect's devastating effects. Mary Ann Fajvan, a research forester for the U.S.D.A. Forest Service, suggested that there are three potential silvicultural options for managing hemlock forests at risk of an HWA infestation: 1) thinning hemlock stands using crop tree management, 2) a shelterwood regeneration method, and 3) doing nothing (Abraham 2015). These options do not necessarily prevent an HWA infestation event from occurring, but they do make the changes post-HWA infestation potentially more gradual, lessening the risk of hazards from hemlock snags in popular recreational areas, and offering landowners an opportunity to make a monetary profit from hemlock timber. Preemptive harvests of hemlock prior to HWA infestation, however, reduce the likelihood of potentially HWA-resistant hemlocks surviving and producing HWA-resistant progeny (Orwig & Kittredge 2005).

Chemical controls have been developed for use on high-value trees, e.g., the application of insecticides that include imidacloprid, dinotefuran, acetamiprid, and thiamethoxam (Havill et al. 2014). These are effective systemic insecticides that can be applied through soil injection or drenches and trunk injections (Havill et al. 2014). Horticultural oils and insecticidal soap sprays have also been used, and must coat all insects on the tree to be effective; therefore, they are impractical on large trees (Ward et al. 2014). In general, chemical treatments are reserved for high-value hemlock trees in ornamental settings because of the high cost of insecticides and the need to perform repeated treatments on the trees (Ward et al. 2014).

Biological control of HWA offers a promising future, such as with the introduction of beetles in the genus *Laricobius* Rosenhauer. *Laricobius nigrinus* Fender, a beetle native to western North America which feeds solely on HWA in that region and was introduced into eastern North America in 2000, would offer hope of controlling HWA (Havill et al. 2014). In 2012, *Laricobius osakensis* Montgomery & Shiyake was released into eastern North America, as this *Laricobius* beetle is native to southern Japan and has been seen to feed more effectively on the Japanese strain of HWA that is present in eastern North America (Havill et al. 2014). Because these beetles have only recently been released and have not had sufficient time to increase their numbers to levels that may negatively affect their HWA prey, their effectiveness in controlling HWA is not yet known (Havill et al. 2014). There is also a beetle, *Laricobius rubidus* LeConte, which is native to eastern North America, that primarily feeds on the pine bark adelgid (*Pineus strobi* Hartig) and only on HWA if the pine bark adelgid is unavailable (Havill et al. 2014). Beetle introduction may be a viable mechanism for controlling HWA at the forest level in Alabama; however, their introduction must occur before HWA populations become so large that a predatory beetle cannot be effective.

Table 3.1. Forest Vegetation Simulator (FVS)-predicted change in basal area (BA; m^2/ha) for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama (hemlock woolly adelgid infestation year =2024). Control represents FVS-predicted changes with no infestation.

Year	Hemlock BA	Total BA	Hemlock BA (Control)	Total BA (Control)
2015	18	43	18	43
2020	19	44	19	44
2025	5	30	21	47
2030	2	29	23	49
2035	0	30	24	49
2040	0	32	25	49
2045	0	34	26	49
2050	0	35	27	49
2055	0	37	28	49
2060	0	38	28	49
2065	0	40	29	49
2070	0	41	30	49
2075	0	42	31	49
2080	0	43	31	49

Table 3.2. The top four tree species groups (% of trees per hectare) predicted by the Forest Vegetation Simulator (FVS) in 2015 and 2080 for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama (hemlock woolly adelgid infestation year =2024).

Year	**Species 1**	**Species 2**	**Species 3**	**Species 4**
2015	*Tsuga canadensis* (57%)	*Quercus montana* (13%)	Other hardwoods (6%)	*Quercus alba* (4%)
2080	*Quercus montana* (30%)	*Quercus alba* (11%)	Other hardwoods (9%)	*Ostrya virginiana* (8%)

Table 3.3. Forest Vegetation Simulator (FVS)-predicted change in basal area (BA; m^2/ha) for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama (hemlock woolly adelgid infestation year =2027). Control represents FVS-predicted changes with no infestation.

Year	Hemlock BA	Total BA	Hemlock BA (Control)	Total BA (Control)
2015	18	43	18	43
2020	19	44	19	44
2025	21	47	21	47
2030	16	43	23	49
2035	11	38	24	49
2040	1	28	25	49
2045	0	30	26	49
2050	0	31	27	49
2055	0	33	28	49
2060	0	35	29	49
2065	0	36	29	49
2070	0	37	30	49
2075	0	39	31	49
2080	0	40	31	49

Table 3.4. The top four species groups (% of trees per hectare) predicted by the Forest Vegetation Simulator (FVS) in 2015 and 2080 for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama (hemlock woolly adelgid infestation year =2027).

Year	Species 1	Species 2	Species 3	Species 4
2015	*Tsuga canadensis* (57%)	*Quercus montana* (13%)	Other hardwoods (6%)	*Quercus alba* (4%)
2080	*Quercus montana* (31%)	*Quercus alba* (11%)	*Pinus taeda* (8%)	Other hardwoods (8%)

Table 3.5. The top four species groups (% of trees per hectare) predicted by the Forest Vegetation Simulator (FVS) in 2015 and 2080 for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama given no hemlock woolly adelgid infestation (hemlock woolly adelgid infestation year =2024).

Year	Species 1	Species 2	Species 3	Species 4
2015	*Tsuga canadensis* (57%)	*Quercus montana* (13%)	Other hardwoods (6%)	*Quercus alba* (4%)
2080	*Tsuga canadensis* (81%)	*Quercus montana* (6%)	*Pinus taeda* (3%)	*Fagus grandifolia* (3%)

Table 3.6. The top four species groups (% of trees per hectare) predicted by the Forest Vegetation Simulator (FVS) in 2015 and 2080 for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama given no hemlock woolly adelgid infestation (hemlock woolly adelgid infestation year =2027).

Year	**Species 1**	**Species 2**	**Species 3**	**Species 4**
2015	*Tsuga canadensis* (57%)	*Quercus montana* (13%)	Other hardwoods (6%)	*Quercus alba* (4%)
2080	*Tsuga canadensis* (81%)	*Quercus montana* (6%)	*Pinus taeda* (3%)	*Fagus grandifolia* (3%)

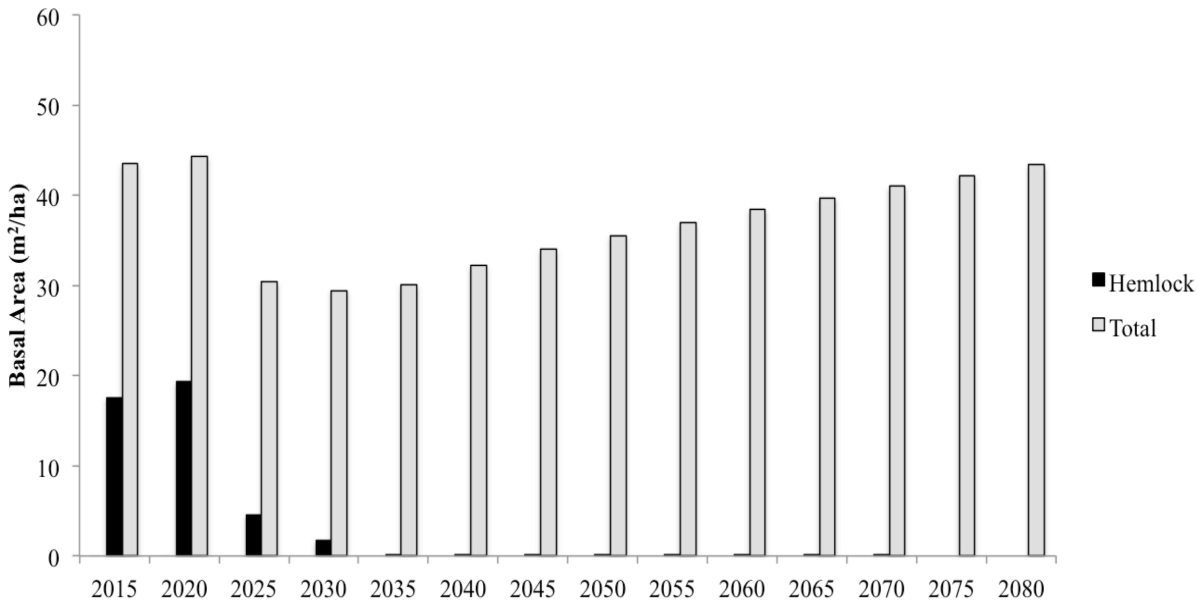

Figure 3.1. Forest Vegetation Simulator (FVS)-projected change in total basal area and hemlock basal area (hemlock woolly adelgid infestation year =2024) for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama 65 years into the future.

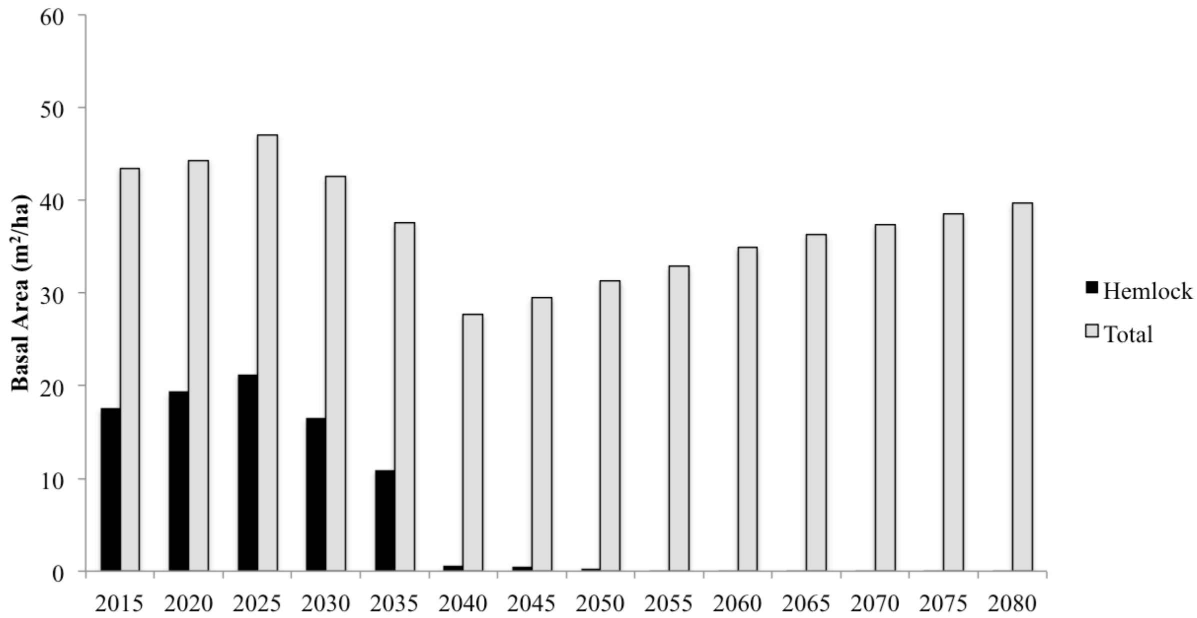

Figure 3.2. Forest Vegetation Simulator (FVS)-projected change in total basal area and hemlock basal area (hemlock woolly adelgid infestation year =2027) for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama 65 years into the future.

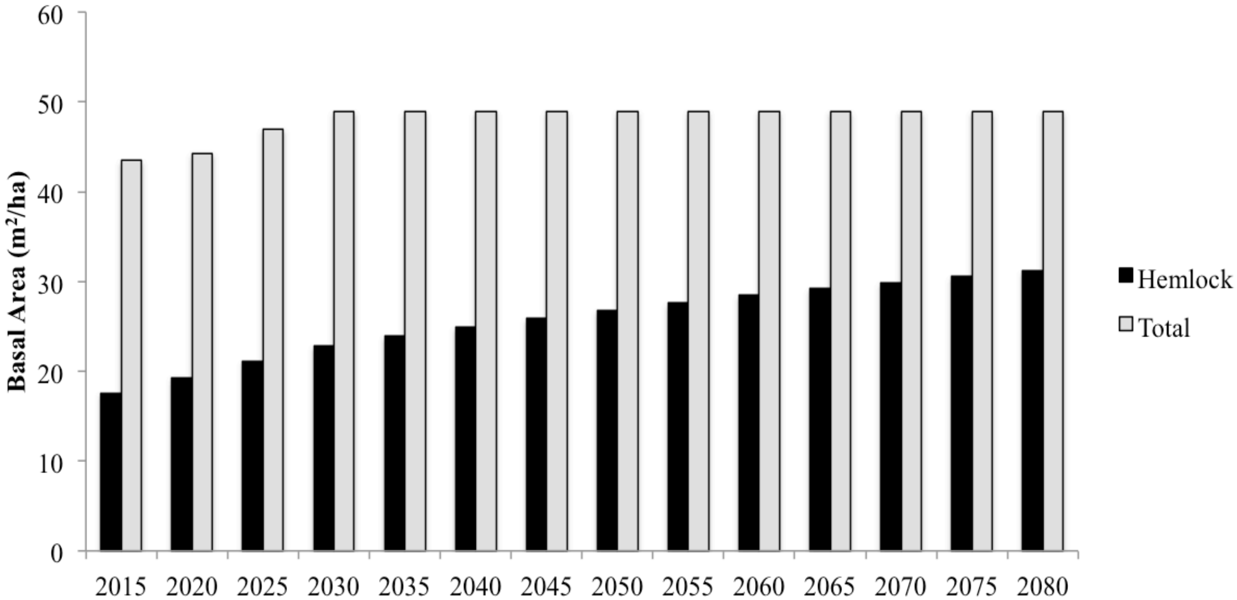

Figure 3.3. Forest Vegetation Simulator (FVS)-projected change in total basal area and hemlock basal area (hemlock woolly adelgid infestation year =2024; no infestation control) for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama 65 years into the future.

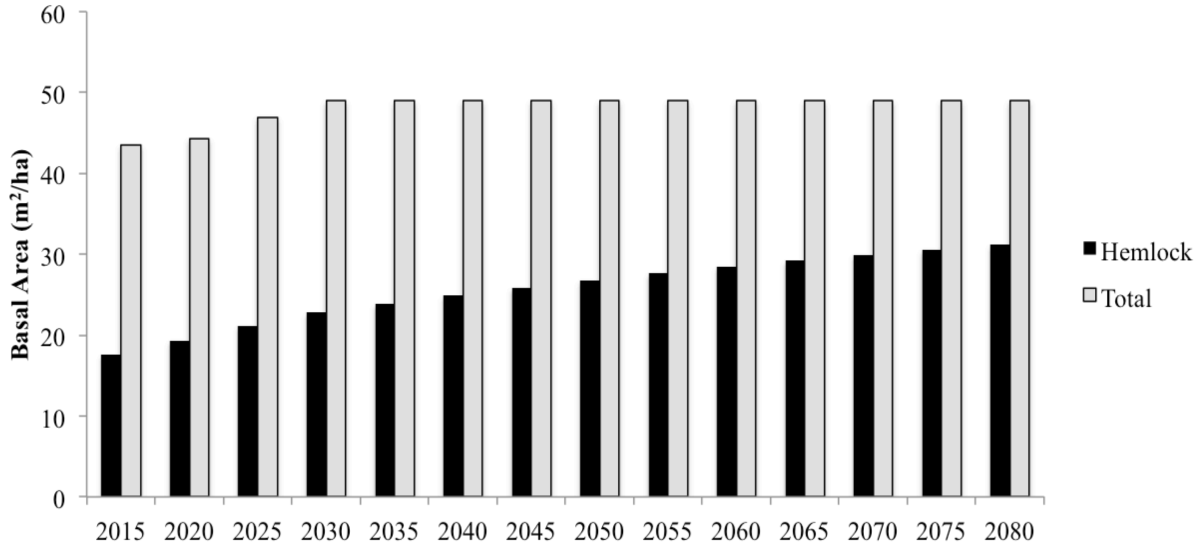

Figure 3.4. Forest Vegetation Simulator (FVS)-projected change in total basal area and hemlock basal area (hemlock woolly adelgid infestation year =2027; no infestation control) for the hemlock-dominated forest on the William B. Bankhead National Forest in northwestern Alabama 65 years into the future.

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Appendix A: Tree Data

Appendix A. Trees (> 10.0 cm DBH) inventoried in the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama. Crown classes (adapted from Smith et al. 1997) defined as follows: dominant (D), codominant (C), intermediate (I), overtopped (O), snag (S).

Plot	Species	DBH (cm)	Crown Class
1	*Quercus montana*	38.5	C
1	*Fagus grandifolia*	29.2	I
1	*Acer rubrum*	15	I
1	*Acer rubrum*	11.2	O
1	*Tsuga canadensis*	37.5	C
1	*Quercus alba*	35.4	C
1	*Quercus alba*	31.9	C
1	*Tsuga canadensis*	20.9	C
1	*Tsuga canadensis*	16.8	I
2	*Tsuga canadensis*	25.9	C
2	*Pinus taeda*	58.7	D
2	*Quercus montana*	37	C
2	*Tsuga canadensis*	27.2	C
2	*Tsuga canadensis*	24.4	C
2	*Tsuga canadensis*	13.8	I
2	*Quercus alba*	46.8	D
2	*Tsuga canadensis*	13.8	I
2	*Tsuga canadensis*	13.7	I
2	*Tsuga canadensis*	20.5	C
2	*Tsuga canadensis*	28.9	C
2	*Tsuga canadensis*	31.5	S
2	*Quercus montana*	41.5	D

Continued

Appendix A Continued

Plot	Species	DBH (cm)	Crown Class
3	*Tsuga canadensis*	24.1	C
3	*Quercus alba*	40.6	D
3	*Tsuga canadensis*	15.8	S
3	*Tsuga canadensis*	12.6	I
3	*Tsuga canadensis*	33.5	C
3	*Tsuga canadensis*	14.1	I
3	*Tsuga canadensis*	12.7	I
3	*Tsuga canadensis*	23.6	C
3	*Tsuga canadensis*	18.1	I
3	*Tsuga canadensis*	20.9	I
3	*Quercus montana*	59.1	D
3	*Tsuga canadensis*	34.4	C
4	*Tsuga canadensis*	33.4	D
4	*Tsuga canadensis*	13.5	I
4	*Tsuga canadensis*	20	I
4	*Tsuga canadensis*	17.5	S
4	*Carya* spp.	15.2	C
4	*Carya* spp.	16.1	C
4	*Quercus coccinea*	30.3	C
4	*Quercus coccinea*	30.6	C
4	*Tsuga canadensis*	26.8	C
4	*Carya spp.*	12.8	I
4	*Quercus coccinea*	29	D
4	*Fagus grandifolia*	32.5	C
4	*Tsuga canadensis*	46.5	D
4	*Tsuga canadensis*	10.3	I

Continued

Appendix A Continued

Plot	Species	DBH (cm)	Crown Class
5	*Pinus taeda*	47.3	D
5	*Tsuga canadensis*	21	C
5	*Tsuga canadensis*	20.5	C
5	*Quercus montana*	23.1	C
5	*Tsuga canadensis*	21	S
5	*Tsuga canadensis*	13.1	I
5	*Tsuga canadensis*	12.6	O
5	*Quercus montana*	38.1	D
5	*Tsuga canadensis*	35.9	D
5	*Tsuga canadensis*	16.7	I
5	*Quercus alba*	32.8	D
5	*Quercus alba*	24.5	C
5	*Tsuga canadensis*	41.5	D
5	*Tsuga canadensis*	18.3	I
5	*Tsuga canadensis*	31.9	S
5	*Tsuga canadensis*	19	I
5	*Quercus alba*	31.9	C
5	*Pinus taeda*	45.2	D
6	*Tsuga canadensis*	18	I
6	*Quercus coccinea*	51.1	D
6	*Tsuga canadensis*	17	I
6	*Magnolia macrophylla*	15.7	I
6	*Quercus montana*	17	I
6	*Tsuga canadensis*	21.2	I
6	*Quercus montana*	34	C
6	*Tsuga canadensis*	21.9	C
6	*Tsuga canadensis*	18.5	I
6	*Quercus alba*	15	I
6	*Tsuga canadensis*	12.2	O
6	*Tsuga canadensis*	15.5	I
6	*Tsuga canadensis*	18.5	I
6	*Quercus montana*	17	O
6	*Liriodendron tulipifera*	21	C
6	*Tsuga canadensis*	17.9	C
6	*Tsuga canadensis*	13.7	I
6	*Quercus montana*	27.3	C
6	*Tsuga canadensis*	19.9	I
6	*Tsuga canadensis*	17.3	I

Continued

Appendix A Continued

Plot	Species	DBH (cm)	Crown Class
7	*Quercus alba*	21.4	C
7	*Pinus taeda*	60.6	D
7	*Tsuga canadensis*	12.4	I
7	*Tsuga canadensis*	13	I
7	*Quercus montana*	22	I
7	*Tsuga canadensis*	10.9	I
7	*Tsuga canadensis*	19.2	I
7	*Tsuga canadensis*	14.2	I
7	*Quercus alba*	43	C
7	*Tsuga canadensis*	24.4	C
7	*Quercus montana*	18.2	C
7	*Tsuga canadensis*	10.5	I
7	*Tsuga canadensis*	14	I
7	*Magnolia macrophylla*	12.7	I
7	*Tsuga canadensis*	22.2	C
7	*Tsuga canadensis*	16.9	I
8	*Tsuga canadensis*	17.9	C
8	*Acer rubrum*	11.5	I
8	*Quercus montana*	13	I
8	*Acer rubrum*	13.4	I
8	*Tsuga canadensis*	16.4	I
8	*Tsuga canadensis*	21.1	C
8	*Tsuga canadensis*	21.9	C
8	*Tsuga canadensis*	15	I
8	*Tsuga canadensis*	15.4	I
8	*Tsuga canadensis*	15	C
8	*Tsuga canadensis*	19.5	I
8	*Tsuga canadensis*	11.5	O
8	*Magnolia macrophylla*	16.5	I
8	*Tsuga canadensis*	16.8	C
8	*Quercus montana*	41.8	D
8	*Tsuga canadensis*	19.4	C
8	*Pinus taeda*	52.7	D

Continued

Appendix A Continued

Plot	Species	DBH (cm)	Crown Class
9	*Quercus montana*	42.2	D
9	*Quercus montana*	30.5	C
9	*Quercus montana*	18.3	I
9	*Tsuga canadensis*	67	D
9	*Tsuga canadensis*	16.5	I
9	*Quercus montana*	18.9	I
9	*Quercus montana*	41.2	D
9	*Quercus montana*	20.7	C
9	*Diospyros virginiana*	20.5	I
9	*Tsuga canadensis*	23.9	I
9	*Tsuga canadensis*	23.5	I
9	*Tsuga canadensis*	12.9	I
9	*Quercus montana*	65.4	D
9	*Tsuga canadensis*	15.5	O
9	*Quercus montana*	16.1	I
9	*Magnolia macrophylla*	15.7	I
9	*Tsuga canadensis*	11	O
9	*Tsuga canadensis*	10.8	I
9	*Tsuga canadensis*	12	I
10	*Tsuga canadensis*	20.8	I
10	*Tsuga canadensis*	12.6	I
10	*Quercus montana*	21.1	I
10	*Quercus montana*	33.8	C
10	*Quercus montana*	26.4	C
10	*Tsuga canadensis*	12.1	I
10	*Tsuga canadensis*	11.7	I
10	*Tsuga canadensis*	10.9	O
10	*Quercus montana*	17.8	I
10	*Tsuga canadensis*	10.8	O
10	*Quercus montana*	20.3	C
10	*Tsuga canadensis*	13.2	O
10	*Tsuga canadensis*	18.1	I
10	*Tsuga canadensis*	11.3	I
10	*Quercus montana*	38.6	C
10	*Tsuga canadensis*	16.1	I
10	*Tsuga canadensis*	21.9	C
10	*Tsuga canadensis*	19.3	C

Appendix B: Large Saplings Data

Appendix B. Large saplings (2.5-10.0 cm DBH) inventoried in the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama.

Plot	Species	DBH (cm)
1	*Ostrya virginiana*	3.7
1	*Ostrya virginiana*	4.1
1	*Ostrya virginiana*	10
1	*Tsuga canadensis*	3.1
1	*Ostrya virginiana*	3.5
1	*Ostrya virginiana*	6.9
1	*Tsuga canadensis*	3.4
1	*Ostrya virginiana*	6.1
2	*Fagus grandifolia*	6.9
3	*Tsuga canadensis*	8.7
4	*Tsuga canadensis*	7.8
4	*Tsuga canadensis*	10
4	*Tsuga canadensis*	4.2
4	*Tsuga canadensis*	4.2
4	*Ostrya virginiana*	7.4
4	*Ostrya virginiana*	8.4
4	*Ostrya virginiana*	9.3
4	*Tsuga canadensis*	9.3
5	*Tsuga canadensis*	2.6
5	*Tsuga canadensis*	4
5	*Kalmia latifolia*	4.5
5	*Kalmia latifolia*	3
5	*Kalmia latifolia*	3.5
5	*Kalmia latifolia*	3.5
5	*Kalmia latifolia*	4.2
5	*Carya* spp.	4.5

Continued

Appendix B Continued

Plot	Species	DBH (cm)
6	*Tsuga canadensis*	9.7
6	*Tsuga canadensis*	4.5
6	*Tsuga canadensis*	3.7 (dead)
6	*Tsuga canadensis*	3.5
6	*Tsuga canadensis*	4
6	*Cornus florida*	9.2
6	*Tsuga canadensis*	6.7
6	*Tsuga canadensis*	7
7	*Tsuga canadensis*	4.7
7	*Acer rubrum*	8.2
7	*Fagus grandifolia*	9
7	*Tsuga canadensis*	7.9
7	*Tsuga canadensis*	9.2
7	*Tsuga canadensis*	6.5
7	*Tsuga canadensis*	7.5
7	*Tsuga canadensis*	5.9
8	*Quercus montana*	3.1
8	*Kalmia latifolia*	4.5
8	*Kalmia latifolia*	4.7
8	*Kalmia latifolia*	5.1
8	*Tsuga canadensis*	5.8
8	*Tsuga canadensis*	5.8
8	*Tsuga canadensis*	6
8	*Tsuga canadensis*	3.9
8	*Tsuga canadensis*	7.5
8	*Magnolia macrophylla*	2.5
9	*Magnolia macrophylla*	4.5
9	*Kalmia latifolia*	4
9	*Kalmia latifolia*	5.1
9	*Kalmia latifolia*	3.9
9	*Kalmia latifolia*	2.8
9	*Magnolia macrophylla*	2.6
9	*Tsuga canadensis*	10

Continued

Appendix B Continued

Plot	Species	DBH (cm)
10	*Tsuga canadensis*	3.7
10	*Tsuga canadensis*	5.3
10	*Tsuga canadensis*	7.9
10	*Tsuga canadensis*	8.1
10	*Tsuga canadensis*	6.7
10	*Acer rubrum*	8.1
10	*Ilex opaca*	4.5
10	*Fraxinus* spp.	4.8
10	*Kalmia latifolia*	3.5
10	*Hamamelis virginiana*	2.9
10	*Ilex opaca*	9.1

Appendix C: Small Saplings Data

Appendix C. Small Saplings (≥ 1.0 m tall, <2.5 cm DBH) inventoried in the ten 200-m^2 plots on the William B. Bankhead National Forest in northwestern Alabama. No small saplings were found in plots 1, 2, and 3.

Plot	Species	Tally
4	*Tsuga canadensis*	7
4	*Carya* spp.	1
5	*Acer rubrum*	1
5	*Ilex opaca*	1
5	*Magnolia macrophylla*	2
6	*Quercus montana*	1
6	*Magnolia macrophylla*	1
6	Unknown	3
6	*Ilex opaca*	1
7	*Acer rubrum*	1
7	*Ilex opaca*	3
7	*Tsuga canadensis*	3
7	*Magnolia macrophylla*	1
8	*Kalmia latifolia*	2
8	*Carya spp.*	1
8	*Magnolia macrophylla*	3
8	*Ilex opaca*	2
8	*Tsuga canadensis*	1
9	*Kalmia latifolia*	3
9	*Acer rubrum*	1
9	*Ilex opaca*	3
9	*Tsuga canadensis*	1
9	*Kalmia latifolia*	1
10	*Tsuga canadensis*	6
10	*Kalmia latifolia*	7
10	*Ilex opaca*	1
10	*Magnolia macrophylla*	1

Appendix D: Seedlings Data

Appendix D. Seedlings (<1 m tall) inventoried in the ten 8-m^2 nested plots on the William B. Bankhead National Forest in northwestern Alabama.

Plot	Species	Tally
1	*Quercus montana*	63
1	*Acer rubrum*	14
1	*Quercus alba*	3
2	*Quercus montana*	7
2	*Quercus alba*	4
3	*Quercus montana*	26
3	*Quercus alba*	2
4	*Tsuga canadensis*	2
4	Unknown	3
4	*Acer rubrum*	3
5	*Quercus alba*	2
5	*Acer rubrum*	2
5	*Smilax* spp.	3
5	*Ilex opaca*	3
5	Unknown	3
5	*Kalmia latifolia*	2
6	*Acer rubrum*	25
6	*Toxicodendron radicans*	3
6	*Quercus coccinea*	1
6	*Cornus florida*	2
6	Unknown	1
6	*Quercus montana*	1
7	*Smilax* spp.	6
7	*Acer rubrum*	5
7	*Quercus montana*	2
7	*Quercus rubra*	1
7	*Ilex opaca*	2
8	*Quercus rubra*	1
8	Unknown	6
8	*Ilex opaca*	2
8	*Acer rubrum*	4

Continued

Appendix D Continued

Plot	Species	Tally
9	*Quercus coccinea*	5
9	*Acer rubrum*	3
9	*Quercus montana*	1
9	*Smilax* spp.	1
9	*Kalmia latifolia*	4
10	*Smilax* spp.	3
10	*Kalmia latifolia*	1